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# DEVELOPMENT AND VALIDATION OF A METHOD OF EVALUATING THE EFFECTIVENESS OF FIGHTER AIRCRAFT SIMULATION FORCE CUEING DEVICES

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**13. ABSTRACT** *(Maximum 200 words)*
This report documents the study which developed a method for evaluating the effectiveness of various force cueing devices in a flight simulator. The concept developed included measurement of pilot behavior, performance, physiology and subjective pilot opinion to evaluate system effectiveness.

As a part of this study, a trial evaluation was conducted in a laboratory fighter simulator to validate the evaluation method including identifying which pilot behaviors could best be measured and how the data could be collected and analyzed. Five task scenarios were flown by experienced fighter pilots with and without the presence of force cueing. Control activity and vehicle state data were analyzed to examine the effects of force cueing on pilot performance and control behavior. A debriefing questionnaire was used to elicit the pilot's subjective evaluation. The results of the trial evaluation indicated that the presence of force cueing improved pilot performance, control behavior, and made the simulator more operationally realistic.

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## FOREWARD

As the fidelity increases for tactical aircraft training simulation devices, especially visual simulation, the contribution of Force Cueing needs to be established. The pilot in a fighter aircraft is constantly experiences various forces on the body. These forces provide cues, consciously and unconsciously, about the accelerations of the aircraft resulting from pilot control input, the environment and aircraft state including failures. In a static simulator, these cues are not present.

In a simulator with force cueing devices, such as motion platform, dynamic seat, G-suit, etc., the contribution of force cues to pilot performance and training is virtually unknown. The issue of Force Cueing contribution for tactical aircraft training devices has been unanswered for twenty-five years. As the use of training devices increases and as these devices are being used for combat training and rehearsal, the contributions of force cueing need to be established to ensure that the combat pilot behavior and performance in the simulator will be as close as possible to what as experienced in the aircraft.

As a result of an initial force cueing study conducted for the US Air Force by SIMTEC, Inc., Manassas, Virginia, it was concluded that the effectiveness of potential force cueing devices could only be determined by evaluation in a mission context with experienced operational pilot. The Air Force had already successfully performed similar operational evaluations of visual combat simulators, under a program referred to as "Vis-Eval" using these same ground rules. Based upon the success of these efforts, it appeared logical that a force evaluation (Force-Eval) process might be useful for evaluation of force cueing devices. However, it was recognized that force cueing effects are much more subtle and harder to isolate than visual cues and, therefore, would be more difficult to evaluate. Because of this difficulty and other factors, such as the pilots may be unaware of changes in their control strategy as a function of force cueing, it was determined to be essential that a force cueing evaluation be based largely on objective data collection.

This purpose of the current study effort was to develop a method for evaluating the effectiveness of various force cueing devices in a flight simulator. The concept developed included measurement of pilot behavior, performance, physiology and subjective pilot opinion to evaluate system effectiveness.

A Trial Force-Eval was conducted in a fighter simulator to validate the method including identifying which pilot behaviors could best be measured and how the data could be collected and analyzed. Five task scenarios were flown by experienced fighter pilots with and without the presence of force cueing. Control activity and vehicle state data were analyzed to examine the effects of force cueing on pilot performance and control behavior. A debriefing questionnaire was used to elicit the pilot's subjective evaluation. The results of the Trial Force-Eval indicated that the presence of force cueing improved pilot performance, control behavior, and made the simulator more operationally realistic.

The authors thank Mr. Gary Hellmann and Mr. Dan Caudill of the Air Vehicles Directorate, Air Force Research Laboratory for their assistance and support in providing simulator setup, operations and facility support during the preparation and performance of the Trial Force-Eval.

# SECTION 1 INTRODUCTION

The use of ground based training devices for fighter aircraft in the United States Air Force (USAF) has principally been limited to emergency procedures, part task, and non-visual mission training. For that reason, the need for force cueing has also been limited. Attempts in the past to use force cueing devices, such as platform motion and dynamic seats, have met with limited success for a variety of reasons including poor hardware performance, ineffective drive algorithms and excessive transport delays.

As the USAF transitions into tactical combat mission training using multiple networked simulators, the requirement for force cueing needs to be assessed. The contribution of force cueing in training simulators is not well understood. The Commander of Air Combat Command, during a Distributed Mission Training conference in July 1997, expressed concern that without force cueing, pilots would pull nine or ten g's in a simulator without being aware that they were doing so.

The objective of a training simulator is to allow the pilot to develop, experience and reinforce the techniques and habit patterns that will be needed for correct performance in the aircraft. Generally, for any task in the aircraft, there are unique sets of critical cues to which a pilot responds in order to accomplish the task. Pilots are very adaptable. If the proper cues are not provided in a simulator that would be normally use in the aircraft, the pilot will find other cues in order to accomplish the task. This generally does not result in optimal performance and may lead to different control strategies than used in the aircraft. Obviously, this is not optimal for training since the pilot is simply learning to fly the simulator rather than the aircraft and may have to later relearn in the aircraft.

The evaluation of force cueing is difficult. Pilots largely do not understand which force cues they use or how they use them while flying the aircraft. In the simulator, the pilots cannot always articulate the impact of incorrect or missing force cues on their performance or control strategy. Thus, an analytical evaluation method is needed to determine the contributions of various force cueing devices in a tactical training simulator.

The purpose of this program was to develop a method for conducting force cueing evaluations. The program included a Trial Force-Eval that was conducted to validate that evaluation method. This method includes both procedures and criteria for evaluating the effectiveness of various force cueing devices, such as platform motion systems, dynamic seats, etc., for tactical mission simulation. The Trial Force-Eval included a dynamic seat referred to as the ALCOGS, actuation of the pilot's anti-g suit and Combat Edge. Combat Edge is a positive pressure breathing system used on current fighter aircraft. Supporting the Trial Force-Eval was a simplified fighter cockpit with F-15C dynamics, a limited field-of-view rear projection screen display and an Evans and Sutherland 4530 Image Generator. The Trial Force-Eval was conducted at the Control Integration and Assessment Branch Simulation Facility, Air Vehicles Directorate, Air Force Research Laboratory, Wright Patterson AFB, Ohio.

After the completion of this Trial Force-Eval, a complete evaluation needs to be accomplished on a simulator which includes a full spectrum of force cueing devices such as performance platform motion, a dynamic seat, and a full field of regard visual system. This Force-Eval should determine the contributions of the various force cueing technologies, individually and in combinations, in a simulated combat mission training environment.

This report will describe an overall approach to the development of an evaluation method and a Trial Force-Eval, which examined a representative subset of the overall evaluation method.

## SECTION 2 APPROACH

Ideally, the determination of the need for training device capability would be made based on transfer of training studies. However, evaluations that isolate the effects of different capabilities of a simulation device on training are difficult to develop and implement.

An alternative to transfer of training studies is to evaluate force cueing effectiveness subjectively, similar to the USAF Vis-Eval program. Vis-Eval uses highly experienced instructor pilots to fly tactical missions in candidate visual simulators. These pilots rate the potential of the visual system to support student training of each task within representative combat missions (Brown, 1994). In applying this technique, it must be recognized that the effects of force cueing are often subtle and, in many cases, may not be outwardly recognized by the pilot. Another method to evaluate force cueing effectiveness is to measure differences in pilot performance with and without different force cueing inputs. However, this technique by itself may not be sufficient since pilots may compensate for the lack of certain cues by altering their control strategy. A pilot may not be aware that he or she is compensating for the lack of forces that would normally be present in the aircraft. Outwardly, performance without force cueing may be similar to what takes place in the aircraft (or a simulator with adequate cueing); however, pilot behavior in the form of control strategy may be far different than the aircraft. In essence, the pilot may be learning to fly the simulator and later have to relearn in the aircraft.

What appears to be an optimum approach to evaluating force cueing devices is to measure a combination of changes in pilot performance, physiology, behavior and subjective opinion while flying a simulator with and without different force cue inputs during typical tactical missions. It is possible to analyze how the lack of force cues and the presence of different simulated force cues affected pilot behavior and performance as compared to full body force cueing in the aircraft. This can be accomplished by comparing data taken in the simulator with data taken in the aircraft while performing similar missions and maneuvers.

The Trial Force-Eval did not have the luxury of having available flight testing to collect data which then could be used as a standard to compare with simulator data. Therefore, the effects of force cueing could only be compared by the presence or lack thereof in the simulator.

The approach taken to develop and validate an evaluation method to determine effectiveness of force cueing devices was conducted using several steps. The first step was to identify potential cueing devices that could become part of the Trial Force-Eval within the limits of the program. Four such devices were identified including (1) a dynamic seat referred to as the ALCOGS, (2) the Combat Edge positive pressure breathing system, (3) anti-g suit and (4) Clark Audio transducer. A detailed description of these devices is provided in Section 5, "Trial Force-Eval System and Evaluation".

The Clark Audio transducer was not included in the Trial Force-Eval because of limited quality of the source data representing the aircraft's audio range. This was a disappointment since the transducer appeared to have great potential as a low cost means of providing force cue inputs such as cobble stone effect during ground operation, weapon firing effects, system actuation and higher frequency information such as engine operation.

Concurrently with the effort to select the devices that would form the basis for the Trial Force-Eval, an analysis was conducted to identify and tabulate the different forces encountered in a fighter aircraft. The results are documented in Section 3, "Types and Effects of Force Cues Associated with Fighter Aircraft".

Since the purpose of the effort was to develop a method for evaluating force cueing effectiveness, it was necessary that criteria be established to decide what was and was not effectiveness. Section 4, entitled "Criteria for Determining Force Cueing Effectiveness", discusses the various criteria which were explored and later validated.

Once the cueing devices were identified for the Trial Force-Eval, steps were taken to integrate them into a fighter simulation system. This system consisted of F-15 aerodynamics, a generic fighter cockpit with appropriate controls and avionics systems. For a description of the hardware used for the Trial Force-Eval, refer to Section 5 entitled "Trial Force-Eval System and Evaluation".

Development and evaluation of drive algorithms were a critical part of the Trial Force-Eval. The drive algorithms, more than hardware performance, determines the effectiveness of force cueing systems. Expert engineering pilots and simulation specialists worked together using a trial and error procedure to define and refine the algorithms. The most critical system requiring the greatest amount of effort was the dynamic seat. Algorithms developed earlier for this seat did not address problems encountered when the seat was used in a full tactical mission environment. As an example, tracking algorithms that appeared to work well in a 1-g environment did not work at all well when high-g pursuit tracking was performed.

From the beginning of the program it was recognized, that not all flight tasks or portions of the aircraft flight envelope would be sensitive to force cueing. Therefore, tasks scenario had to be chosen where forces would conceivably have an effect on the pilot's behavior and/or performance. Task scenarios are discussed in Section 5. Instrumentation is another important area where trial and error was necessary to determine what data would produce useful information.

The Trial Force-Eval was conducted with a limited number of highly experienced fighter pilots. Performance data, control behavior and subjective data were analyzed to identify differences between a mission flown with and without force cueing. Descriptive statistics were computed to investigate differences. Power spectral analyses were performed on stick activity to identify differences in control behavior. Subjective debriefing questionnaires were reviewed and summarized.

## SECTION 3 TYPES AND EFFECTS OF DIFFERENT FORCE CUES ASSOCIATED WITH FIGHTER AIRCRAFT FLIGHT

Force cues experienced in a fighter aircraft vary in frequency from the low frequency high-g sustained forces associated with high performance maneuvering to audio frequency range vibrations. The Force-Eval covered the full range of force cueing stimulus. It examined the application of different devices that may provide the pilot with useful cues. In addition to differences in frequency, force cues may also be broken down other ways such as maneuver cues and disturbance cues. Maneuver forces or motion may be defined as that motion that arises within the control loop as a result of flight control inputs by the pilot. Disturbance forces or motion, on the other hand, arise outside of the control loop as a result of atmospheric turbulence or failure of some component of the aircraft that causes an unexpected motion of the aircraft. Disturbance cues also result from changes in aircraft state such as firing of stores or actuation of systems such as dive brakes.

Force cues are generally perceived by three human sensors; visual, vestibular and tactual. The pilot senses motion from the visual scene information by vection. Vection is an illusionary sensation of self-motion produced by translatory motion of the visual scene. The sensation that you are moving when stopped at a stop light caused by perceiving the car next to you moving in the periphery may be classified as a vection cue. Vection cues are said to be more powerful when the visual translation occurs in the distance and in the periphery (Boff, 1988).

Acceleration inputs are provided by the vestibular system (imbedded in the temporal bones on each side of the head near the inner ear) which includes the semi-circular canals and the otolith organs. For extremely small maneuver corrections, the forces may be too small to be sensed by the vestibular system. The minimum threshold at which acceleration is sensed by the vestibular system is approximately 0.3 degrees per second per second (Boff, 1988).

Tactual inputs include touch that is mediated by receptors in the skin (tactile input) and sense of movement and position of the limbs and other body parts, arising from stimulation of receptors in joints, muscles, and tendons (kinesthetic).

In the aircraft, the pilot has access to the input of all three sensors. Although they may often provide redundant inputs to the brain, these inputs tend to reinforce each other. The reaction time of the vestibular and tactual input appear to be faster than the visual input (Boff, 1988).

### 3.1 Sustained Maneuver High-g Forces

High-g maneuvers result in very low frequency maneuver cueing. The sustained high-g maneuvering of a fighter aircraft significantly affect the pilot's performance and physiology. Few of the force cues associated with high-g maneuvering can effectively be simulated in a ground-based trainer. Some of the effects associated with these forces include:

(1) Blood Pooling - During high-g maneuvering, the blood pools in the lower extremities which may lead to loss of consciousness. The anti-g suit worn by the pilot provides counter-pressure forces through inflation to reduce blood pooling. During such maneuvering, the counteracting forces between the body and the anti-g suit provide the pilot with cues as to relatively how much g force the aircraft is pulling. In a simulator, the g-suit can be activated to provide sustained g force cues to the pilot. However, the amount of force applied by the suit must be scaled down since the forces of the blood are not working against the g-suit forces.

Another device worn by the pilot in some fighter aircraft to counteract the effects of high-g forces is the Combined Advanced Technology Enhanced Design G Ensemble (Combat Edge). Combat Edge, is shown in Figure 2. It consists of (1) a positive pressure breathing system, (2) a bladder fitted to the rear inside of the flight helmet which pulls on a strap to hold the oxygen mask in place during high-g maneuvering and (3) an inflatable chest bladder to apply pressure to the pilot's chest during high-g maneuvers.

An anti-g suit together with the Combat Edge was activated during the Trial Force-Eval.

(2) Pilot Pressed Into Seat - During high-g maneuvering, g forces press the pilot into the seat, applying pressure on the buttocks and the thighs. In addition, when the pilot is pressed into the seat, his eyepoint is slightly lowered. The dynamic seat provides the pilot with an indication of the increased pressure being applied to the buttocks and a lowering of eye height. During the Trial Force-Eval, inflating the seat bladder increased buttock pressure.

(3) Pilot Limbs Become Heavy - In the aircraft, the pilot's arms and legs become extremely heavy during high-g maneuvering and it becomes difficult to move in the cockpit. Generally, the pilot is able to move around, but must do so differently. There has been some experimentation in simulators to apply loading to the pilot's limbs through attachment of devices such as cables that restrict the pilot's movement. Such devices have generally been found very cumbersome.

(4) Increased Head and Helmet Weight - The pilot's head and helmet, like the limbs, increase in weight proportional to the number of g's pulled in the aircraft.

This increase makes it difficult for the pilot to turn his or her head. This also puts a strain on the neck. Efforts have been made to artificially force load the pilot's helmet during simulated high-g maneuvering (Ashworth, 1978).

(5) Effects of High-g Forces on Vision - During high-g maneuvering, blood flows to the lower extremities causing a loss of vision. This loss of vision happens in two stages starting with degradation of peripheral vision resulting in tunnel vision and finally a total loss of vision or blackout. Individual pilot's resistance to loss of vision varies as function of conditioning, training and recent experience. In addition, shorter pilots generally have an advantage over taller pilots because of the shorter distance from the brain to the heart. It is possible in a simulator to provide the gray out/blackout effect by dimming the visual system and, with certain visual display hardware capabilities, simulate the tunnel vision effect. A problem with simulation of these effects is that it is difficult to vary the onset of these vision loss effects since they are a function of individual pilot resistance. In the aircraft, the pilot is able to delay the effect of vision loss by performing the "M-1" maneuver, a straining and grunting action to increase tolerance to high positive vertical acceleration. A method for sensing through myoelectric signals when the pilot is performing the maneuver and varying loss of a vision as a function of the straining has been proposed (Albery, Gum, 1978).

### 3.2 Disturbance Forces

Disturbance force cues result from aircraft motion that is independent of the pilot's inputs to the flight control system. These cues take different forms including turbulence, buffet, ground effects, or vibration. Disturbance cues may be either correlated or uncorrelated. Correlated disturbances are a result of an event such as an engine out, dive brake deployment, etc. They provide the pilot with an alerting cue that an event has taken place. Uncorrelated disturbances such as turbulence are not related to an event and therefore do not provide the pilot an alerting cue. Such cues can cause fatigue and increase workload.

#### 3.2.1 Buffet

Buffet results from airflow across the aircraft surfaces causing an aerodynamic disturbance that moves the aircraft. Buffet cues are correlated disturbances, which provide information on current conditions such as angle of attack and airspeed. They also provide feedback as to current configuration and configuration changes, i.e. landing gear, flaps, stores, speed brakes, etc. Buffet can provide the pilot with critical alerting cues.

### 3.2.2 Ground Effect

Ground effects are non-turbulent forces on the aircraft, which are experienced at approximately one half of one wingspan in altitude. Ground effects are very low in frequency. In most modern fighter aircraft, the pilot is taught to maintain a constant angle of attack during an approach to landing and to ignore any ground effects. Therefore, ground effects may not be considered as critical a cue as it would be in many earlier aircraft. However, ground effect force cue simulation may be important in order to train the pilot to ignore them. Ground effects like buffet could be considered correlated disturbances since it occurs in a particular part of the flight envelope.

### 3.2.3 Vibration

Vibrations are higher frequency forces such as engine vibrations induced into the airframe, stores vibrations, and cooling turbine vibrations. Normally, vibrations would be considered non-correlated disturbances. However, sudden or recognizable changes in vibration could provide an alerting cue and be considered a correlated disturbance cue. These could include events such as detection of a engine malfunction or confirmation of an event such as firing of a gun. Vibration can cause fatigue. Under certain conditions, it can also cause some degradation of a pilot's visual performance. Time to interpret a display can increase as a result of vibrations depending upon the frequency and intensity.

### 3.2.4 Turbulence

Turbulence is a non-regular atmospheric disturbance acting on the airframe. It is of varying frequency and amplitude. Its frequency generally ranges at or below that of buffet. Turbulence may be classified as a non-correlated disturbance. It increases pilot workload and makes flight tasks such as target tracking and flight control during low level high-speed flight more difficult.

## 3.3 Audio Frequency Forces

Auditory cues are sensed by not only the pilot's ears, but by proprioception. Audio frequency forces overlap with vibration forces. In the aircraft, the pilot perceives audio frequency forces associated with the aircraft such as engine noise/vibration, actuation of control systems and deployment of weapons. They may be perceived by the ears and/or felt through the limbs (including bone conduction, skin, and possibly by the chest diaphragm). Audio forces may be either a correlated or disturbance cue. Correlated alerting cues include engine malfunction, gun firing, and release of stores. Firing of guns may be both heard and felt, whereas release of stores may be heard and felt as a thump. For the latter, the pilot may also feel the results of change in weight of the aircraft. In a fighter aircraft, audio cues may affect workload and produce stress.

# SECTION 4 CRITERIA FOR DETERMINING FORCE CUE EFFECTIVENESS

The criteria for determining the contribution and effectiveness of force cueing devices may include three factors: (1) pilot behavior in the simulator as compared to behavior in the aircraft, (2) pilot performance in the simulator as compared to performance in the aircraft and (3) pilot subjective perceptions. Other factors may also be considered, such as, the additional stresses which force cueing adds to the simulator environment that may make it more closely resemble the aircraft environment.

Ideally, the criteria used to determine the acceptability of the simulator force cueing should be based on the similarity of pilot behavior in the simulator as compared to behavior in the aircraft. Since there is little behavioral data available concerning performance in the aircraft, it is necessary to rely on analysis by experts for relating the behavioral data gathered in the simulator to what would be expected in the aircraft

## 4.1 Pilot Behavior

If the pilot's behavior in the simulator is similar to that in the aircraft, it is usually agreed that transfer of training to the aircraft should occur. This does not mean that some positive transfer will not occur in many cases where behavior is different. Lack of appropriate force cues in a simulator can change pilot behavior in the simulator. Other differences in the simulator, such as workload and stress, can also effect behavior and training. The Trial Force-Eval examined how measurement of pilot behavior may be used as a criterion for force cue evaluation. Insight regarding the effect of force cues can be obtained by examining behavioral data with and without the presence of force cues.

### 4.1.1 Control Strategy

Indications are that lack of force cueing in a simulator can affect the way a pilot flies a simulator as compared to the aircraft. He or she may adapt different control strategies than those used in the aircraft if the simulator lacks motion or other force cueing. This may result in relearning the tasks in the aircraft.

### 4.1.2 Eye Scan Response

Without the appropriate force cues, a pilot will still respond to vection cues provided by the visual system. However, it appears that the rate at which a pilot responds to vection without the appropriate force cues may lag that in the real world aircraft (Boff, 1988). Force cues, although they may not duplicate the real world, may speed up eye response to more closely resemble eye response in the aircraft. Measurements could be made with an oculometer to compare eye movement response with and without appropriate force cues. No such measurements were made during the Trial Force-Eval.

### 4.1.3 Pilot Control Input Bandwidth

The rate at which a pilot inputs control responses may be referred to as the pilot's control bandwidth. A pilot responds to force cues more rapidly than to visual cues alone. If the pilot does not receive adequate force cues, the rate of control response increases thus reduced bandwidth. Therefore, for certain tasks, pilot control bandwidth is a good measure of the adequacy of the force cues. During the Trial Force-Eval, pilot bandwidth was measured and compared with and without force cueing.

### 4.1.4 Pilot Cue Reliance

Without force cueing, the pilot will be forced to search for and rely on other cues. As an example, he or she may have to check on engine RPM gauge rather than feeling a change in vibration or will be forced to check the g-meter rather than feel the change in g-force. Such changes in visual scan patterns relative to the pilot's scan pattern in the aircraft, may cause the pilot to learn spurious habit patterns.

### 4.2 Pilot Physiological State

The presence or absence of force cueing can effect the pilot's physiological state. This may include heart rate, blink rate, respiration, and EEG. Generally, it is expected that the addition of force cueing will increase these factors because of increases in workload and stress. However, there may be some cases where force cueing reduces workload, which may reduce the physiological stress on the pilot.

### 4.2.1 Workload and Stress

A pilot must deal with many different stressors during a tactical mission. Typical stressors include electronic combat environment, low altitude turbulence, radio chatter, etc. Generally, the force cueing environment in an aircraft provides increased stress on the pilot. This stress may be caused by increased task difficulty resulting from turbulence and high-g forces. It could also be caused by the added realism of the simulation resulting from having a more real world like environment when force cueing is added to the simulation. Stress can have an immediate effect on behavior and performance.

### 4.2.2 Fatigue

Turbulence or buffet causes an increase in workload, which may cause fatigue. This can be a longer-term effect on the pilot during a mission.

### 4.3 Pilot Performance

Pilot performance is a second measure of force cueing effectiveness in a simulator. In many cases, the difference in performance with different force cueing inputs makes performance a reliable criterion for evaluating force cue effectiveness. However, in other cases, performance by itself is not a reliable measure since the pilot may be using alternate cues and/or adapting a different control strategy in order to compensate for a lack of certain cues in the simulator. In such cases, the performance results in the simulator may be very similar to the aircraft. However, from a training standpoint this may be less than fully acceptable since the pilot may have to relearn tasks using the proper cues in the aircraft. In such cases, it is important to measure behavior along with performance. Areas where measurement of performance appears to be appropriate are provided in the subparagraphs. In some cases, performance alone as a criterion may be appropriate whereas, in others, behavior along with performance must be measured.

#### 4.3.1 Tracking Measures

Positional, rate and temporal accuracy are all good measures of performance of different flight tasks. These need to be selectively measured and compared for different force cueing configurations.

#### 4.3.2 Accuracy of Flight Profile

Differences in the flight profile for specific maneuvers, as a function of differences in force cueing may be useful in determining the effect of force cueing on pilot performance. Typical examples include maintaining low altitude and performing ridge crossings. Flight profile may be more directly interpretable than changes in position, rate and temporal accuracy data.

#### 4.3 3 Pilot Subjective Perceptions

Experienced training system engineers can gather pilot subjective perceptions using questionnaires and structured pilot debriefings/interviews. For the Trial Force-Eval, the pilots completed a structured questionnaire following an evaluation mission. Following completion of the questionnaire, the pilots were debriefed using the questionnaire.

## SECTION 5 TRIAL FORCE-EVAL SYSTEM AND EVALUATION

The Trial Force-Eval system was developed by the Air Force Research Laboratory and Middendorf Scientific Services Inc., which included all simulator systems and data collection equipment. This system consisted of the computational system, software, cockpits, avionics, visual image generator, visual data base and visual display, the force cueing hardware and dynamic seat drive algorithms, the operator control systems and displays, and the instrumentation.

### 5.1 Trial Force-Eval System Capabilities

#### 5.1.1 Computational System

The Trial Force-Eval system used three Encore RSX computers for the simulation executive and simulation model processing. Each RSX computer was a single processor that communicates with the other RSX computers via a reflective memory bus. The simulation executive was configured to run synchronized with the image generation system at a 60 Hz frame rate. Most software processes were run at the 60 Hz rate while some of the slave tasks were run at 30 Hz. The following table indicates what simulation software was running, rate it was scheduled to run, and processor where each task was located.

**Table 1. Simulation Software**

| Computer System | Processor # | Software/Process | Rate |
|---|---|---|---|
| Encore RSX (J) | 1 | Sim Executive | 60Hz |
| | | Hardware I/O | 60Hz |
| | | Wind / Turbulence | 60Hz |
| | | Aircraft #1 (F-15 Model) | 60Hz |
| | | Aircraft #2 (Playback) | 60Hz |
| | | IG Driver | 60Hz |
| | | HUD Driver | 60Hz |
| | | HDD Driver | 60Hz |
| | | Data Capture | 30Hz |
| Encore RSX (G) | 1 | ALCOGS Driver | 60Hz |
| | | G-suit / Combat EDGE | 60Hz |
| | | Truth Sensor | 60Hz |
| | | Fire Control | 60Hz |
| Encore RSX (F) | 1 | 20mm Gun | 30Hz |
| | | Reticle | 30Hz |

### 5.1.2 Graphics Computers

The Trial Force-Eval system used two Silicon Graphics computers for graphic display processing of the cockpit head down display and HUD imagery. These graphic systems were driven through an Ethernet ring that operates asynchronous from the rest of the simulation. Data packets were updated by the simulation display drivers, at the rate at which they were scheduled, then sent to the graphics processors for interpretation and the graphic displays, then update as fast as they could upon receiving those data packets.

### 5.1.3 Image Generator

The Trial Force-Eval system used one Evans & Sutherland model 4530 image generator for generating and controlling the out the window (OTW) visual scene at the simulator station. A Whidbey Island database was utilized for the terrain scene. The simulation was configured to run synchronously with the image generator at a 60 Hz frame rate. A Mig-29 moving model was used to represent the second aircraft. The only unusual image generation capability incorporated in the Trial Force-Eval system was the ability to create a 3-dimensional pathway in the sky using partial tank models as pathway markers. This implementation was dubbed the "Pylon Course". It was a series of diamond shaped hoops that the test aircraft is required to fly through at the proper orientation. Each hoop was a set of five turretless T-72 tank bodies. The hoops were arranged in a diamond formation centered on the intended flight path as shown in Figure 1.

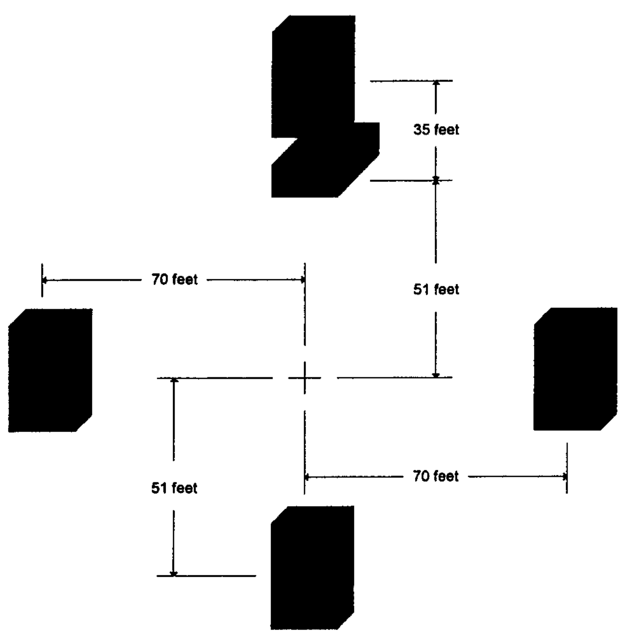


Figure 1. Pylon Course Hoop.

### 5.1.4 Visual Display

Original plans called for the integration of the force cueing devices into the facility's MS-1 large dome simulator station; however, the visual fidelity was not sufficient to support all required Trial Force-Eval tasks. Instead, a rear projection screen that had been set up for initial checkout and dynamic seat algorithm development was used for the Trial Force-Eval. This display had a field-of view (FOV) 64 degrees wide by 50 degrees high. The imagery was rear projected with a General Electric light valve projector onto a 8 by 10 foot screen in front of the cockpit. HUD graphics were video mixed with the visual scene. This provided the simulator station with OTW visual and HUD flight data.

### 5.1.5 Simulator Cockpit Station

The simulator cockpit station used for the Trial Force-Eval was built from various simulator components specifically for the evaluation. The cockpit itself was built around the ALCOGS force cueing seat by mounting an F-15 throttle quadrant on the left armrest and a side stick with F-15 grip on the right armrest. The side stick was a force stick, similar to an F-16 side stick that generates stick inputs based on force measurements with very little motion from the stick itself. Head down instruments was displayed on a high resolution, 29-inch monitor located directly in front of the ALCOGS seat. This monitor was located to provide the pilot with a 15-degree over-the-nose-viewing angle with respect to the OTW imagery.

### 5.1.6 Simulation Software

The simulation executive was a FORTRAN program that allows for the scheduling and activation of all of the simulation components across multiple computers and processors. The individual components were written in FORTRAN, C, C++ or ADA. This executive allowed the simulation operators to create schedules for all of the simulation components based on whole, even multiples of the base simulation frame rate, which was 16.6667 ms (60 Hz).

### 5.1.7 Simulation Models

The aircraft model that was utilized in the simulation was a 6 degree of freedom (DOF), high fidelity model of an F-15C. This model was written in FORTRAN and originated from McDonnell Douglas in support of past flying qualities programs. To reduce the number of variables in the Trial Force-Eval tests, the aircraft model was configured to maintain fixed mass properties and assumed no external stores. A landing gear model was also integrated with the F-15C model to provide the capability to

simulate takeoffs and landings. The model responded to speedbrakes, landing gear, stick and throttle inputs. Rudders were not used.

### 5.1.8 Environment

The Trial Force-Eval system incorporated atmospheric turbulence effects for some landing scenarios. The model used to generate the turbulence was a Winds/Gusts/ Turbulence model that originated from NASA Dryden. The output of this model was incorporated into the aircraft model aerodynamics and equations of motion algorithms to ensure that the aircraft achieved the appropriate dynamic response to the atmospheric disturbances. Turbulence model gust lengths and RMS scales were adjusted to provide moderate turbulence for those test runs that required this effect.

### 5.1.9 Sensors

The Trial Force-Eval system did not require realistic sensor models so a simplistic, truth data radar model was implemented. This model gave the pilot perfect radar track information for the tracked aircraft. This provided the pilot the capability to designate the other aircraft as the primary target and obtain relative geometry information for that aircraft relative to the ownship. This information was displayed on the HDD and HUD displays and only applies to those test scenarios that contain a second aircraft. The radar track data was also required for driving the Lead Computed Optical Sight System (LCOSS) gun reticle during the Air-to-Air gun-tracking task.

### 5.1.10 Weapons

The only weapon utilized in the Trial Force-Eval was a generic 20mm gun model.

### 5.1.11 Situation Display

The Situation Display used two range rings centered on the ownship for range reference lines; one at half of the current display range and the other at full display range. Indicated range was measured from the ownship symbol to the top edge of the display. Tracks were positioned in azimuth on the display along imaginary radial lines that are measured relative to the ownship longitudinal body axis.

### 5.1.12 Weapons Format

The weapons (WPNS) format displayed status of ownship weapons, fuel, and countermeasures. Digital readouts for gun rounds, fuel (lb.), chaff, and flare were provided along with graphical depictions of the Short Range Missiles (SRM) and Medium Range Missiles (MRM) on board the aircraft.

### 5.1.13 HUD

The HUD symbology was essentially the same as the F-15E HUD symbology with modifications to reduce clutter and to meet research Trial Force-Eval needs. MRM, SRM and Gun modes were all supported, although the missile modes were not utilized in these tests. Navigation information was available as well as a continuously computed impact point (CCIP) air-to-ground bombing sight.

### 5.1.14 Flight Controls

The stick and throttles provide aircraft control using an F-15C model. The stick and throttle grips were used to provide the switchology needed for control of the simulated aircraft systems. They provide the pilot immediate access to control of the displays when was not appropriate to use the bezel push-button.

## 5.2 Force Cueing Devices

Force cueing devices used for the Trial Force-Eval were the Advanced Low-Cost g-Cueing System (ALCOGS) dynamic seat, anti-g suit, and Combat Edge Positive Pressure Breathing System. Another device, the Clark Audio Transducer, was considered for the Trial Force-Eval; however, due to problems in obtaining useful data to drive the device, it was not included in the evaluation. Although it was not part of the evaluation, it is addressed briefly in this section of the report.

### 5.2.1 ALCOGS Dynamic Seat

The ALCOGS dynamic seat originally developed by Air Force Human Resources Laboratory (AFHRL) was refurbished and integrated into the evaluation simulator. The ALCOGS includes hydraulic actuators, which provided an active moving seat and three thin cushion surface bladders for localized pressure and tactile area-of-contact stimuli generation. The seat pan has passive thigh ramps and tuberosity stimulating blocks. The seat also included differential lap belt drive and implementation of lower backrest to provide strong area-of-contact cues for vertical and longitudinal acceleration. Table 5.2.1 provides a synopsis of the performance characteristics of the ALCOGS.

#### 5.2.1.1 ALGOGS Seat Refurbishment

Although the ALCOGS is approximately twenty years old, it still represents state-of-the-art with respect to performance. Due to the age of the device, a great deal of refurbishment and testing work had to be completed before the seat could be operated. For the Trial Force-Eval, the seat components were driven in the following manner:

(1) Seat Bladder (pneumatic) - Positive Sustained g's

(2) Back Bladder (pneumatic) - Surge for afterburner, speedbrakes, etc.

(3) Seat Pan Pitch and Roll (hydraulic) - Aircraft Velocity and Acceleration

(4) Backrest Pitch and Yaw (hydraulic) - Aircraft Velocity and Acceleration.

**Table 2. ALCOGS Performance**

| ALCOGS Performance | | | |
|---|---|---|---|
| **Component** | **Axis** | **Excursion** | **Response** |
| Seat Pan | Pitch, Roll,<br>Heave<br>Fore-Aft | +/- 12 degrees<br>+/- 1.25 inches<br>+/- 1.0 inches | 36 ms, 7.3 Hz |
| Backrest | Pitch<br>Yaw<br>Surge | +/- 6 degrees<br>+/- 9 degrees<br>+/- 1.0 inches | 36 ms, 7.3 Hz |
| Backrest Bladder | Roll | 3 psi | < 3 Hz |
| Seat Bladder | Surge | 3 psi | < 3 Hz |
| Seat Shaker | Heave | +/- 0.25 inches | 34 Hz |
| Lap Belt | Fore-Aft | +/- 1.5 inches | 30 ms, 10 Hz |

### 5.2.1.2 ALCOGS Seat Drive Algorithms

The pitch angle of the seat pan and backrest were driven with a combination of aircraft pitch velocity and pitch acceleration. The roll angle of the seat was driven with a combination of aircraft roll velocity and roll acceleration. The yaw angle of the backrest was driven with a combination of sideslip angle and sideslip angle rate.

The drive laws were implemented in such a manner that allowed scaling to be specified as maximum seat movement. For example, the seat pan can roll as much as twelve degrees, but the scaling parameter for roll could be set to only five degrees. The coefficient for the basic drive law was then back calculated using vehicle performance information across a wide range of flight conditions, specifically, mach number. Due to high frequency effects, pitch acceleration had to be ramped out near mach one.

The seat pan bladder was driven with z-axis acceleration for simulating positive g. The original software for this dynamic seat was written so that the bladder pressure was decreased for positive g. This lowered the pilot onto hard blocks to simulate increased pressure on the buttocks. This also lowered the pilot with respect to the rest of the cockpit. For the Trial Force-Eval, the drive law was written so that the bladder pressure

increased with positive g's which increased the hardness of the seat and the perceived force. Although this approach is somewhat counter intuitive, it received consistent approval from pilots during the Trial Force-Eval.

Since there is a tendency for the pilot to sink in the seat during high-g maneuvering, it would be expected that there is a need to lower the pilot's eye height in the simulator. This could have been done with the hydraulic actuators in the seat. However, the Trial Force-Eval pilots did not feel this was necessary.

A similar approach was used for the backrest bladder, which was driven with x-axis acceleration. When the simulated aircraft accelerated, the bladder pressure increased.

### 5.2.2 Anti-g Suit

The Trial Force-Eval included an active anti-g suit as a force cueing device. Since in the 1-g environment of a simulator, there is no blood pooling in the lower extremities during high-g maneuvering, suit pressurization was scaled down. Onset inflation occurred at 2 g, with full inflation to 6.5 psi at 9 g.

### 5.2.3 Combined Advanced Technology Enhanced Design G Ensemble (Combat Edge)

Both the F-15 and the F-16 aircraft are fitted with anti-g Loss of Consciousness (LOC) systems, called Combat Edge, in order to extend the pilot's g-tolerance. Figure 2 provides a sketch of Combat Edge. Combat Edge is designed to provide tactical aircrew members with a positive pressure breathing system for positive vertical acceleration (+4 to +9 g) and protection at altitudes up to 50,000 feet. The system components consist of modified helmet, oxygen mask, vest assembly, breathing regulator and required integration and connection hardware. The Combat Edge equipment is used in conjunction with a standard Air Force anti-g cutaway suit. In the aircraft, the anti g-valve senses the presence of positive g conditions and provides pressurized engine bleed air at a predetermined schedule to the anti g-suit and the oxygen regulator pressure sensor. Regulated air and oxygen at a predetermined schedule is supplied to the Combat Edge equipment to provide vest inflation and positive pressure breathing gas (PPBG) for breathing. The vest is worn on the upper torso of the crewmember over the standard flight suit and provides chest counter pressure during PPBG use. The Combat Edge helmet includes a modification whereby an inflatable bladder is installed to provide the automatic mask tensioning required for PPBG. All elements of Combat Edge, which may conceivably provide useful cues, were activated. Similar to the anti g-suit, Combat Edge required rescaling in order to safely operate in the one-g environment of the flight simulator. Normally, the anti-g suit pressure controls Combat Edge. Because the g-suit pressure was scaled down, a separate electronically controlled g-valve was needed to drive Combat Edge.

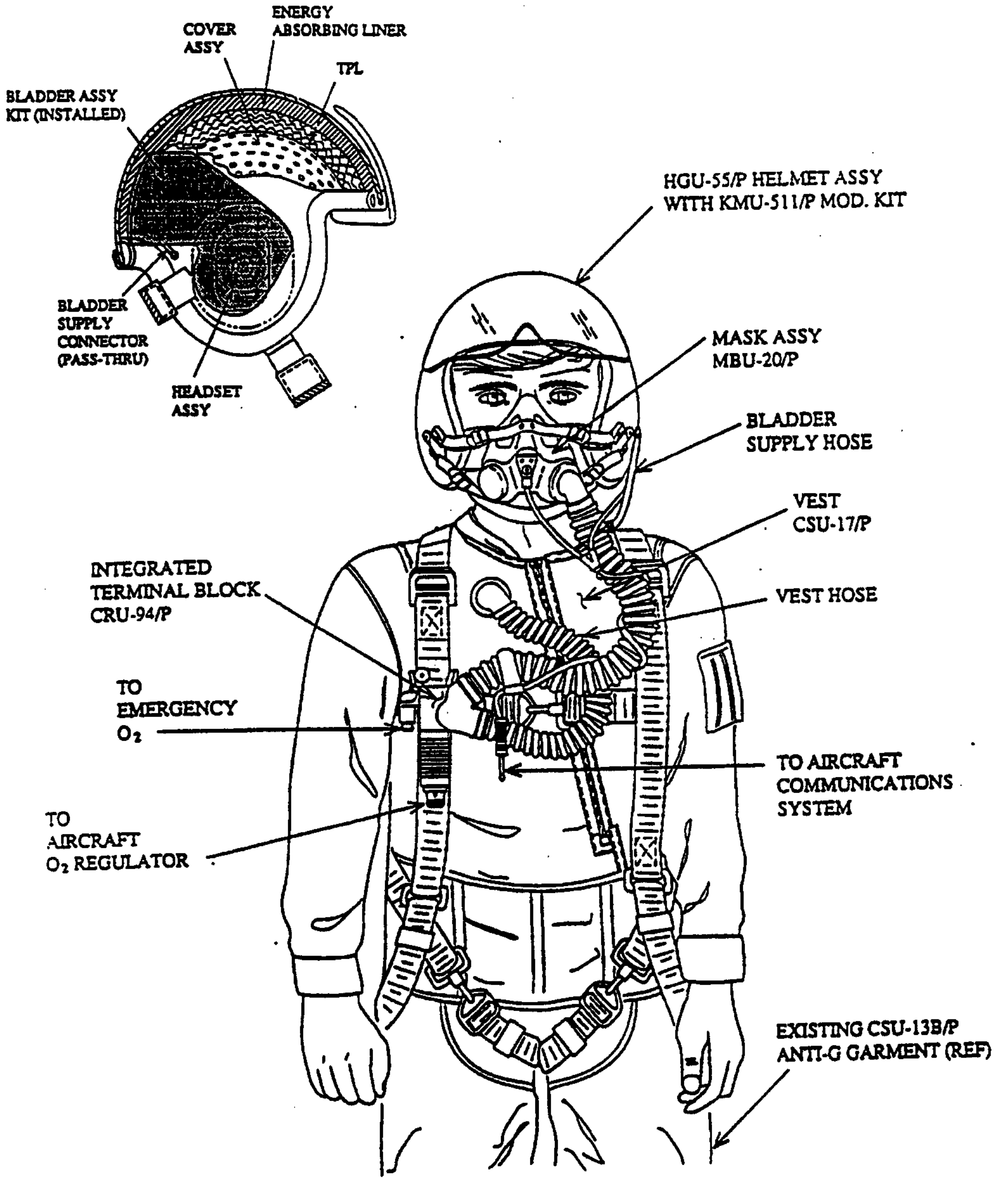


Figure 2. Combat Edge System.

### 5.2.4 Clark Audio Transducer

A high power audio range transducer may provide significant cues to the pilot in a simulator. Clark Synthesis, Inc., of Littletown, Colorado, offers an audio range transducer called the "Clark Absolute Tactical Sound System". This transducer is

approximately 8 inches in diameter and 2 inches high and is mounted on a single 3/8-inch threaded stud. The device is capable of accepting 200 watts RMS power with a transduction force of 1.2 pounds per watt. The frequency range is from 5Hz to 200khz. The transducer is most effective with a highly rigid mounting structure. It appears that only one transducer may be necessary in a simulator.

This device should support a variety of forces which are both heard and felt including: (1) engine vibration, (2) actuation of systems, (3) firing of guns, (4) release of stores, and (5) background audio such as radio chatter.

#### 5.2.4.1 Clark Audio Transducer Integration

Installation of the Clark Transducer is straightforward. It mounts to any surface with a single threaded stud. However, it was quickly learned that driving the device in a manner that takes full advantage of its capabilities for this application is not so straightforward. This transducer will provide a useful output down to as low as 5 Hz. For simulation of many of the important cues associated with an aircraft, such low frequency response is important. However, standard audio amplifiers do not function at such a low frequency. Also, recorded aircraft data that was available to the program was recorded using audio recording equipment that apparently did not function well at such low frequencies. Attempts to compensate for the shortcomings of the recorded data by modification were not successful. A high power linear amplifier was obtained which drove the transducer effectively at the lower frequencies; however, the audio data problem was never resolved. Therefore, the Clark Transducer was not included in the Trial Force-Eval.

### 5.3 Trial Force-Eval Instrumentation

Most of the requirements for data that needed to be recorded could be determined intuitively. These requirements were determined with consultation with expert engineering pilots. When there was a question as to the potential need it was usually decided in favor of recording data until it could be shown that the data was of no value. The following data were selected for recording in the Trial Force-Eval:

1) Flight control and throttle inputs by evaluation pilot (both magnitude and rate).

2) State vectors for each aircraft.
    - Position
    - Linear and angular rates and accelerations for each aircraft.
        = Related to cockpit for evaluation cockpit (includes g, g-rate).
        = Related to either cockpit, center of gravity or center of rotation for other cockpit.

3) Relative linear and angular positions and rates between aircraft with evaluation cockpit as a reference.

4) Commanded Combat Edge pressure.

5) Commanded g-suit pressure.

6) Indicated airspeed/Mach.

7) Indicated and Radar altitude.

8) Speedbrakes: in/out.

9) Landing gear: up/down.

10) Pickle button or trigger depression as well as selected switch positions.

11) Dynamic seat commanded and recorded positions.

12) ALCOGS commanded bladder pressures.

### 5.4 Evaluation Task Scenarios

Task scenarios were chosen which were potentially sensitive to force cueing. They all involved high task loading. With the exception of the pylon course, task scenarios were representative of different portions of a realistic mission.

#### 5.4.1 Landing Task

A landing task was used to evaluate the effectiveness of angular seat cueing on the pilot's performance during approach and touchdown. A moderate to severe turbulence was present on one-half of the trials. Landings were made with and without force cueing. Because of the low-g nature of the task, the only active cueing device during landing was the dynamic seat. Initial conditions were: altitude 1500 feet AGL, aircraft 8 miles out, on centerline, airspeed 193 knots, speed brake out and gear down. The waypoint marker was overlaid on the runway to indicate the approach point, which is 1000 feet down the runway.

The pilots were instructed to decrease airspeed to 155 knots, begin descent at five miles, and maintain a three-degree glideslope. The pilots were told to attempt a minimal sink rate landing. The actual touchdown point could be further down the runway than the 1000 feet approach point. The pilots were also instructed to maintain a wings-level approach while on centerline, specifically in the presence of turbulence. Pilots were

given two practice trials, one with and one without turbulence. Two sessions of eight landing each were performed. The order of the independent variables (cueing and turbulence) was counter balanced.

### 5.4.2 Low Level Flight With Weapon Delivery Task

A low level task with waypoints was used to evaluate the usefulness of force cueing during low-level flight and weapon delivery. This mission was flown with and without force cueing. The force cueing included the dynamic seat, with bladders, Combat Edge and anti g-suit. The initial conditions were: altitude 1000 feet, airspeed 475 knots, speed brake in, gear up, heading 074 degrees and the aircraft 25 miles from waypoint one. The pilots were instructed to fly at the lowest comfortable altitude and maneuver for optimal ridge crossing until they reach waypoint two. This delineates the terrain following segment of the mission. After waypoint two, the pilots performed an offset pop-up weapon delivery task using a CCIP pipper (continuously computed impact point). The pilots were instructed to perform all four-g turns. Pilots were given one practice trial. Two data collection sessions of four missions each were performed. The order of the independent variable (cueing) was counter balanced.

### 5.4.3 Air-to-Air Guns Task

The air-to-air guns task was a medium g-level task which employed a tracking requirement. This scenario was flown with and without force cueing. The force cueing included the dynamic seat, with bladders, Combat Edge, and anti g-suit. The initial conditions were: altitude 10,000 feet, airspeed 448 knots, speed brake in, gear up and target aircraft 1000 feet ahead. The avionics included a lead-computing optical sight system (LCOSS). The pilots were instructed to keep the LCOSS pipper on the target and maintain a distance of 1000 feet. Distance to the target and closure rate was indicated on the LCOSS reticule. Pilots were given one practice trial. Two data collection sessions of four missions each were performed. The order of the independent variable (cueing) was counter balanced.

### 5.4.4 Pylon Course Task

The pylon course task consisted of a "highway in the sky" which was indicated by sets of pylons that were spaced five seconds apart. The location of the pylons was based on a pre-recorded flight by an experienced pilot performing a box maneuver. The g-loading necessary to accurately fly the course increased with time. Specifically, the end of the course was much harder to fly than the beginning. The orientation of the pylons indicated the roll attitude from the pre-recorded flight. A lead aircraft flew the course just ahead of the pilot's simulated aircraft. The force cueing included the dynamic seat, with bladders, Combat Edge, and anti g-suit. The initial conditions were: altitude 10,000 feet,

airspeed 333 knots, speed brake in and gear up with the lead aircraft 1500 feet ahead and accelerating. The pilots were instructed to follow the lead aircraft through the pylon course and match the roll attitude of the pylons. The pilots were given one practice trial. Two data collection sessions of four missions each were performed. The order of the independent variable (cueing) was counter balanced.

### 5.4.5 Formation Flight Task

A formation flight task was a high-gain task which required continual pilot input. The limited field-of-view visual simulation display increased the task difficulty. The flight path of the lead aircraft was based on a pre-recorded flight. Similar to the pylon course, the g loading increased with time. Force cueing included the dynamic seat, with bladders, Combat Edge, and anti g-suit. The initial conditions were: altitude 10,000 feet, airspeed 333 knots, speed brake in and gear up with the trailing aircraft 13 feet down and 60 feet behind the lead aircraft. The pilots were told to maintain the initial relative position throughout the flight. The pilots were given specific references on the display to aid them in maintaining the relative position. These references used the burner cans of the lead aircraft and the HUD symbology on the pilot's display. Pilots were given one practice trial. Two data collection sessions of four missions each were performed. The order of the independent variable (cueing) was counter balanced.

Pilots participated in two data collection sessions. All five of the task scenarios were performed during each session. Four Trials (two with cueing, two without) were conducted for each scenario, except landing which required eight trials due to the turbulence/no turbulence condition. Forty-eight trials were conducted for each pilot.

## 5.5 Data Analysis

Performance data, control behavior and subjective data were analyzed to identify differences between the cueing and no-cueing conditions. Some trials had to be eliminated to remove outliers. These resulted from system failure, pilot error, and operator error. Pilot error included mistakes such as loosing the pylon course and not relocating it. In another case, the pilot increased the following distance in the formation flight task to make the task easier. Two trials were lost due to hardware failure on the visual system. Three trials were lost due to operator error.

Some tasks were divided into segments and the data were analyzed separately. The waypoint task was divided into a terrain following segment and a weapon delivery segment. The pylon data were divided into two segments where the difficulty level increased. The first three miles on the landing approach where the vehicle was in level fight were not included in the analysis.

Descriptive statistics (mean, standard deviation, and RMS) were computed for several aircraft state variables to investigate differences between cueing and no-cueing. Power spectral analysis was performed on stick activity to identify differences in control

behavior with and without cueing. Subjective debriefing questionnaires were reviewed and summarized.

**5.6 Pilots**

All of the pilots used in the Trial Force-Eval had at least 2000 hours in modern fighter aircraft. Additionally, all four have served as instructor pilots and three of the four are still active. The four pilots had experience in the five flight scenarios used in the study. The pilots were given written instructions before performing each scenario to ensure consistency. A checklist was used prior to each test session to make sure all switches and cueing hardware were in the correct configuration.

# SECTION 6 RESULTS OF THE TRIAL FORCE-EVAL

## 6.1 Summary of Pilot Behavior Evaluation

The results of the evaluation of the various tasks flown with and without force cueing are summarized below:

### 6.1.1 Landing Task

The pilots were instructed to maintain a wings-level approach when on centerline. Previous drive law research (McMillan, Cress, etc., 1990) shows that the dynamic seat is very effective for improving this type of attitude maintenance in the presence of turbulence. It was evident from the data that the four pilots did benefit from the presence of force cueing. However, the benefit was much smaller than expected. The pilots were also told to land on centerline. There was an improvement in this measure with force cueing present. This was most likely the result of the tighter approach noted above.

There was an interesting, and unwanted, effect discovered in the stick data. With the turbulence turned off, there was higher stick activity when force cueing was present (figure 3). This effect was consistent for all four pilots. This suggests that there was some degree of biomechanical coupling, which could slightly degrade the performance benefit of the seat. The coupling was most likely caused by the fact that the stick was rigidly mounted (i.e., it did not move in synchrony with the seat). Therefore, seat motion resulted in body motion, which coupled into the stick. Another possible explanation for this stick activity may be that when force cueing is present, the pilot is continually sampling for feedback by providing small stick inputs.

### 6.1.2 Pylon Course Task

There were substantial benefits of force cueing in the pylon course task. When cueing was present, the pilots flew the course more accurately (figure 4), with less stick activity (figure 5) and more realistic stick activity. Specifically, the z-axis g loading had considerably less variance when cueing was turned on. Examination of g profile plots indicated that the pilots were putting in more g commands that were erratic when cueing was off. With cueing present, the pilots commanded more deliberate, and consistent, z-axis loading.

It is reasonable to suggest that the more consistent g loading is attributable to the anti g-suit and Combat Edge activation. The presence of seat motion also seems to be helping the pilots in the pylon task. The variance in the vehicle's angular rates is much lower when cueing is present. This enabled the pilots to fly the course more accurately, which is indicated in the relative geometry measures (relative azimuth and elevation between the lead aircraft and the trailing aircraft).

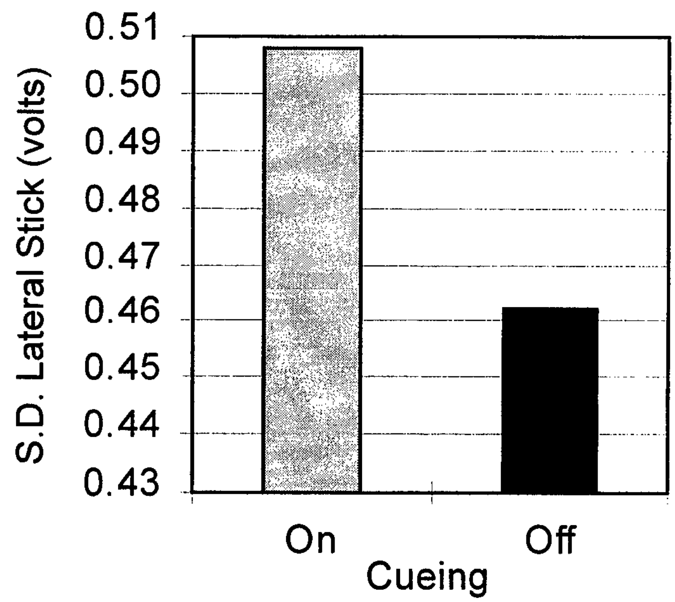


Figure 3. Landing Task. With no atmospheric turbulence, there was higher stick activity when cueing was on. Although this biomechanical coupling is small, it could be problematic if the seat gains were increased. This effect was consistent for all four pilots.

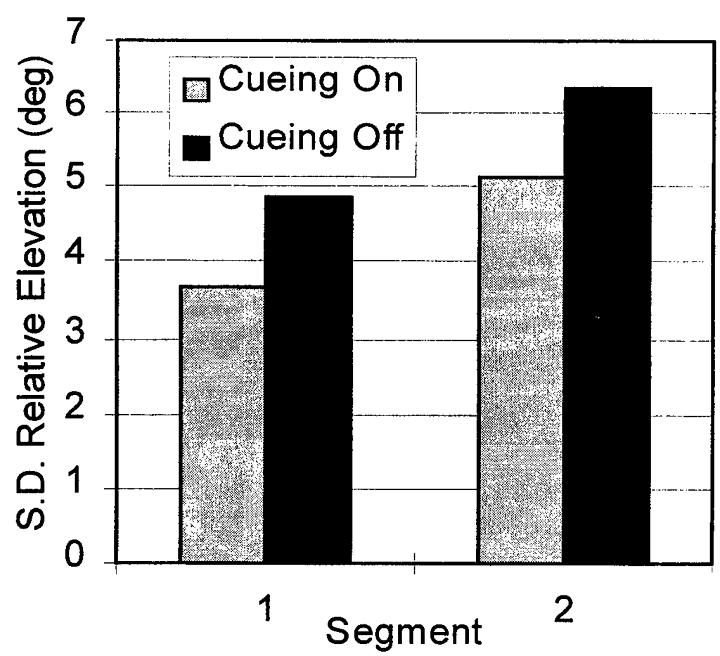


Figure 4. Pylon Course Task. Pilots followed the lead aircraft through the pylon course more accurately when force cueing was turned on. A similar trend was present in relative azimuth. Standard deviation is used because of a large mean due to the following distance.

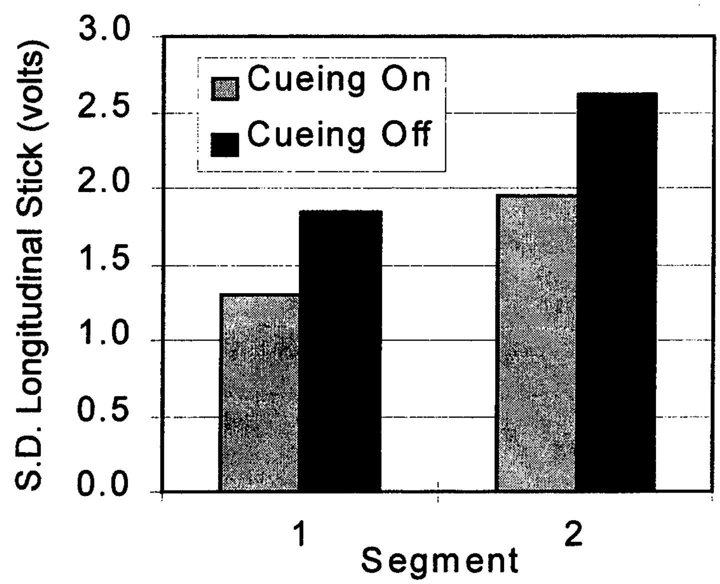


Figure 5. Stick Activity. When force cueing was present, the pilots used less stick activity to fly through the pylon course. The data were divided into two segments at the point where the difficulty level increased.

### 6.1.3 Air-to-Air Guns Task

Air-to-air guns tracking task results were similar to the results experienced with the pylon, however, differences between cueing and no cueing are not as pronounced. This is most likely because the air-to-air guns task requires less g-loading than the pylons task. On average, the pilots did a better job on keeping the pipper on the target when force cueing was present.

### 6.1.4 Low Level Flight Task

Other than a reduction in stick activity, the low-level task with waypoints showed little difference between the cueing conditions during the terrain following segment. There are two reasons for this. First, the task was not demanding in terms of g loading. Three of the four pilots rarely pulled more than two g's for this segment. Second, the instructions to the pilots led to different control strategies. The pilots were told to fly at their lowest comfortable altitude. While one pilot was extremely aggressive in following the terrain, another simply skimmed over the valleys.

### 6.1.5 Formation Flight Task

The main effect of cueing on the formation flight task was seen in the tracking-type measures. These measures include the relative azimuth position off the nose, relative elevation position off the nose, and the relative range (figure 6). The pilots did a

much better job of maintaining the relative position between the two aircraft when the cueing was present. The improvement in relative range may be a result of the thrust feedback provided by the backrest bladder. Additional tests are required to confirm this suggestion.

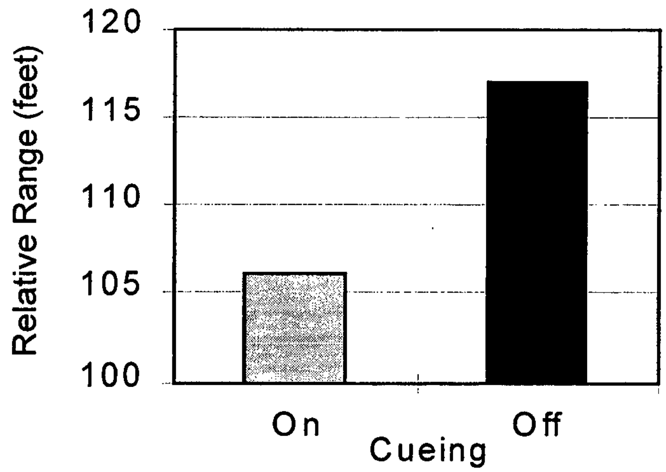


Figure 6. Formation Flight Task. The pilots maintained a closer relative range when force cueing was active during formation flight. The backrest bladder provided thrust feedback.

### 6.2 Power Spectral Analysis of Stick Activity

In the no-cueing condition, there was consistent increased power in the one hertz region on both lateral and longitudinal stick activities. This effect was consistent across the five tasks, but was most pronounced in the formation flight task (figure 7). This is not surprising given the high gain nature of this task. As reported earlier, the pilots performed this task better (relative geometry) when force cueing was turned on. Therefore, the extra power in the one hertz region was not needed to perform the task, and consequently represents remnant and/or artifact. The most likely cause of this unneeded stick activity is due to pilots correcting for over shoot. The dynamic seat provided lead information, which reduced the likelihood of over shoot.

### 6.3 Summary of Pilot Debriefing

When asked "How did the presence of force cueing effect your ability to perform the task?", the pilots agreed that the cueing allowed them to perform the task in a manner closer to how they would perform it in the aircraft. The pilots commented that the cueing provided better/earlier feedback on the effects of flight control inputs. The cueing allowed the pilots to make finer corrections.

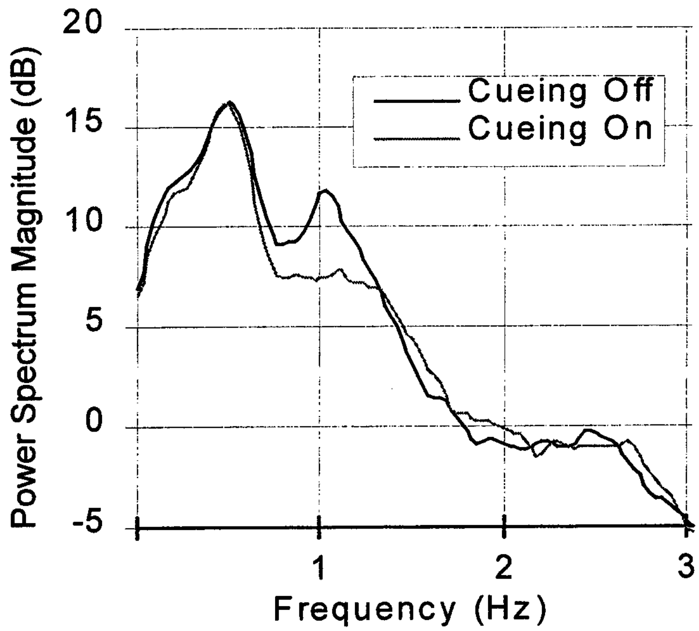


Figure 7. Stick Power Spectral Analysis. The average power spectrum for the four pilots in the formation flight task shows increased power in the one-hertz region when force cueing is turned off.

When asked "Did the force cues enhance the operational realism of the simulator?", there was a strong consensus to the affirmative. In fact, one pilot stated, "it was the closest simulator he has flown and "feels" like real flying." Pilots were asked if there is a force cueing subsystem that could be added that might improve the operational realism of the simulator. Comments varied from no, to maybe, and that the increase in "feel" would not be worth the extra cost and complexity. Limb loading, aural cueing and more longitudinal acceleration were mentioned as possibilities.
Other comments included: this technology could get more pilots to agree that simulators are getting very close to simulating actual flight conditions. If this technology is cost effective, it should be added to all training simulators.

### 6.4 Trial Force-Eval Shortfalls

The results of the Trial Force-Eval indicate the need for improvements in the evaluation process for any future work. These improvements range from simple things such as instructions given to the pilots to more complex issues such as adaptive drive algorithms. For example, the instructions for the low level flight task need to be more definitive so that the pilots will fly in a similar manner. In the landing task, the differences between the cueing conditions were much smaller than anticipated based on previous drive law research. This is most likely due to minimal dynamic seat cueing,

which was a result of the drive algorithms that were normalized across tasks and mach numbers. A follow-on study is needed to evaluate the utility of drive laws that are adaptive to the task.

Some of the tasks would benefit from a larger field of view (FOV) visual display. The limited FOV used in this study caused some trials to be missed in the pylons and air-to-air gun tasks because the pylons (or target) would go off the screen and the pilots could not recover. The limited FOV also imposed constraints on the formation flight task. The lead aircraft had to be set up in a position similar to aerial refueling rather than the typical wingman arrangement.

Other implications for a follow up study include removal of any biomechanical coupling, changes to the turbulence condition in landing, selection of an optimum low level flight course, and the addition of other force cueing devices. It may also be useful to perform workload and physiological recordings and eye tracking recordings.

### 6.5 Observations

#### 6.5.1 ALCOGS Seat Pan Inflation

To simulate positive g forces, the ALCOGS was designed to deflate the pneumatic seat pad. This would lower the pilot's buttocks on to a firm surface, which would increase the pressure on the buttocks thus providing the sensation to the pilot of increased g forces. At the same time, it would reduce the pilot's eye height as if he or she was being pushed down in the seat.

During the process of algorithm development, engineering pilots did not consistently have the perception of increased buttocks pressure by deflating the bladder and being lowered onto the tuberoscity blocks. Although the tuberoscities are the most sensitive part of the buttock, it is not clear that there was an actual increase in pressure. There could be various reasons for this method not consistently providing the proper cues. One problem may be differences in size and shape of pilot buttocks or "one size does not fit all". This may be consistent with what had been experienced at Cranfield (Matthews, 1978)

It was found that by inflating the seat pad, a reliable sensation of increased pressure associated with positive g force could be provided. Also, it would be expected that it would be necessary to lower the seat pan in order to reduce pilot eye height during a high-g maneuver. However, the engineering pilots did not feel it was necessary, although it could easily have been done with the seat hydraulics.

#### 6.5.2 Biomechanical Coupling

The movement of the seat causes relative motion between the pilot and the cock-pit controls. This relative motion may cause unwanted biomechanical coupling. A simulator with a force stick such as the F-16 may be especially vulnerable to such coupling.

## SECTION 7 CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

Evaluating force cueing must be performed in a mission context. Evaluating cueing at the subtask level may prove to be invalid when the full context of the task is added. As an example, during the Trial Force-Eval, it was learned that algorithms developed earlier had only been validated for one-g pursuit. In reality pursuit tracking involves high-g maneuvering in which case these algorithms did not work properly. Consequently, new algorithms had to be developed.

The Trial Force-Eval provides a documented method for future force-cue evaluations. The combination of measured pilot behavior and performance while performing specific tactical mission tasks together with subjective pilot feedback provides an effective means of evaluating the contribution of force cueing to mission performance.

Although the evaluation method does not address how transfer of training may be affected by force cueing, this may not be the real issue. Rather the issue may be whether force cueing will cause the pilot to perform and behave in the simulator similar to the aircraft. Behavior in a simulator, which is far different than the aircraft, may require relearning in the aircraft.

The intent of this program was to develop method for performing simulator force cueing evaluation. The Trial Force-Eval reported here does not, in itself, fully define the method. However, based on the Trial Force-Eval, the following questions should be asked about a force cueing system under evaluation:

(1) Does the system reduce unneeded stick activity in high gain tasks? Does it improve pilot control bandwidth?

(2) Without force cueing in a simulator, pilots tend to pull an unrealistic level of positive g forces and in some case even negative Gs. Do force cueing devices encourage g-profiles that are more realistic?

(3) Does the system provide pitch-axis lead information for high gain pursuit-type tasks (air-to-air guns)?

4) A dynamic seat can provide a longitudinal acceleration cues through the back of the seat. Does the system under evaluation provide thrust feedback (i.e., formation flight)?

## 7.2 Recommendations

The work accomplished under this effort provides a method for conducting force evaluations for tactical combat flight simulation. Although this effort did demonstrate the positive effects of a dynamic seat on pilot behavior and performance, it did not address the impact of other force inputs such as vestibular. It is, therefore, recommended that a force cueing evaluation be conducted on a simulator, which includes a full spectrum of force cueing devices such as the NLR facility at Amsterdam. This simulator includes a high performance platform motion, a dynamic seat, helmet loader and a full field of regard visual system.

The force cue drive laws need to be reviewed to improve cueing effectiveness. Because pilots can have very different control strategies for different mission segments, the gain of the algorithms may need to be adaptive. Additionally, the magnitude of seat and/or platform motion may need to adapt to the task.

The only true method for validating pilot behavior in the simulator is to compare the behavior in the simulator with behavior in the aircraft while performing the same set of maneuvers. Therefore, it is highly recommended that that a flight test program be initiated to collect pilot behavioral data. The Air Force Research Laboratory (AFRL) Variable Stability In-flight Simulator Test Aircraft (VISTA) offers a unique capability to conduct flight test to measure control behavior in the aircraft. This is an F-16C Block 40 aircraft which has been modified to act as a flying test bed. This aircraft has imbedded the instrumentation to make the required measurements.

The Clark Transducer offers a relatively inexpensive method of providing cueing in the frequency range greater than five hertz. Originally, this cueing device was to be included in the Trial Force-Eval. However, it was found that to effectively use this device, high fidelity aircraft data in the five hertz and higher frequency range and a wide band high power linear drive amplifier are required. This data were unavailable. This would best be obtained by making digital recording in a fighter aircraft using the transducer as a pickup device. It is recommended that an evaluation of the transducer be conducted in a simulator using suitable aircraft data.

## APPENDIX A
## RECOMMENDED FORCE EVALUATION SYSTEM

### A-1.0 Evaluation Structure

The success of an evaluation will largely depend on the structure of the evaluation system. The evaluation system included things other than the evaluation hardware, software and instrumentation. These other factors include the mission and task structure and their associated effect on task loading, pilot background, evaluation environment and the structure of the evaluation procedures and how they are conducted.

### A-1.1 Mission Oriented

An effective evaluation program can best be conducted with simulated missions which are representative of what might be expected in the real world aircraft. If the task loading is too low, the pilot may have more time to interpret flight vehicle state information than would be available in the aircraft. Therefore, it is essential that the evaluation be carried out in a task loaded mission environment similar to what is experienced in the aircraft.

### A-1.2 Experienced Fighter Pilots

Highly experienced operational pilots need to be used to conduct an evaluation. Prior to the start of a formal evaluation, experienced training system pilots with a fighter aircraft background were used to assist in development and to conduct preliminary evaluations of the force cueing algorithms, evaluation missions, tasks, data collection equipment and collection procedures.

### A-1.3 Controlled Evaluation Environment

For an evaluation it is essential that the same simulator configuration be maintained throughout an evaluation. However, prior to a formal Force-Eval, it is necessary to change the configuration of the evaluation system in order to look at the effects of differences in algorithms, types of force cueing, changes in instrumentation, changes in mission tasks, and changes in evaluation procedure. Such changes are essential to optimizing the evaluation procedures/method.

### A-1.4 Evaluation Tasks/Subtasks

The evaluation should be conducted in a mission environment. Specific task segments, which appear to be sensitive to the force environment, need to be identified and

later updated. These subtasks should be closely monitored during the evaluation for the effect that different force cue inputs may have on the pilot's behavior and performance.

**A-2.0 Evaluation Facility**

**A-2.1 Facility Data Recording Capabilities**

The simulation facility should have the capability to record in real-time the following types of data:

1) Flight control and throttle inputs by evaluation pilot (both magnitude and rates).

2) State vectors for each aircraft.

3) Linear and angular rates and accelerations for each aircraft.
   - Related to the cockpit for the evaluation cockpit (include g, g-rate).
   - Related to either cockpit, center of gravity or center of rotation for other cockpit.

4) Relative linear and angular position and rates between aircraft with evaluation cockpit as a reference.

5) Evaluation pilot look angles to other aircraft or target (head and eye angles) or target/selected reference/other aircraft angles and rate of closure.

6) G-suit pressure or commanded pressure.

7) Evaluation of pilot head and eye tracking.

8) Pilot physiological state data (heart, respiration, EEG (brain wave), etc.).

9) Indicated airspeed/Mach.

10) Indicated and Radar altitude.

11) Speedbrakes in/out.

12) Pickle button or trigger depression as well as selected switch positions.

13) Force cueing device movement, acceleration and pressure, and lap belt tension.

14) Flight path recordings.

### A-2.2 Visual System

A visual system capable of processing and displaying a highly detailed tactical database including multi level texture is essential for a force cueing evaluation. The visual display must have a wide field-of-view in order to provide vection cues to the pilot. The visual system must provide the fidelity and cues required for low altitude flight, judging closure, and other visual tasks in order that the effects of force cueing may effectively be determined without being effected by inadequate visual cueing. A visual database must be available which provides typical topography for low altitude missions over rough terrain.

### A-3.0 Evaluation Missions/Maneuvers

Since the ultimate goal of a force cueing evaluation is to determine the usefulness of force cueing for tactical combat training simulation, tactical missions must be used for an evaluation. Guidance with respect to potential mission tasks and maneuvers is provided below.

### A-3.1 Types of Missions/Tasks

1) Air-to-air combat.
2) Air-to-ground combat.
3) Aerial refueling/close formation.
4) Landing and takeoff.
5) Pylon course.
6) Variation.
   - Day versus night.
   - Low versus medium altitude.

### A-3.2 Potential Force Sensitive Maneuvers

Although an evaluation is to be conducted in a mission context, it is expected that the pilot's performance of certain tasks and maneuvers will be more sensitive to force cueing inputs than other tasks. A list of potential maneuvers is provided below:

1) Closure on other vehicle.
2) Maintain separation (position) on other vehicle.
3) Maintain low altitude.
4) Perform ridge crossing.

5) Avoid threat.
6) Pull up into pop-up.
7) Track airborne target.
8) Track ground target.
9) Pull out after ground attack.
10) Pitch/roll captures.

### A-3.2.1 High Gain Tracking

A force evaluation should include looking at the effect of different force cues on performance of high gain tracking tasks. Several are provided below in the order of their importance. These tasks may be performed with and without turbulence.

#### A-3.2.1.1 Close Formation, refueling, etc.

Performing tasks such as establishing and maintaining position during close formation and possibly aerial refueling is one of the highest gain tasks. It may be affected by small subtle force cues such as surge and heave.

#### A-3.2.1.2 Air to air combat weapons delivery.

Tracking of another aircraft leading to air-to-air combat weapons delivery is one of the higher gain tactical combat tasks. This task should be performed with various levels of disturbance cues.

#### A-3.2.1.3 Air to Ground Weapons Delivery.

Tracking of a ground target leading to delivery of a weapon is also a high-gain tracking task similar to air to air target tracking.

#### A-3.2.1.4 ILS

An ILS approach and landing is a relatively high gain task. In addition to turbulence, this may be performed with a crosswind.

### A-3.2.2 Maintain/Change Flight Path

The tasks associated with maintaining and changing the flight path of an aircraft are generally lower gain than the tasks discussed under 3.2.1. However, the pilot, may be significantly sensitive to force cues during performance of such maneuvers.

### A-3.2.2.1 Low Altitude Flight

A low altitude mission will be flown with different force cue configurations. This may include both terrain following and terrain avoidance. Performance factors may include altitude maintenance, ability to perform ridge crossing, etc. Behavior and performance should be compared for different force cue inputs.

### A-3.2.2.2 Slalom Course

Although a slalom course may not be representative of the real world, it was shown during the Trial Force-Eval to provide an effective tool for evaluating a force cueing system. Pilots should be required to fly through an airborne slalom course made up of pylons. Force cueing conditions can be varied and pilot performance and may be compared for the different force cue inputs. Although the slalom course is not part of a tactical mission, it may provide insight as to the effect of various force cues on pilot performance during this general type of aircraft maneuvering.

### A-4.0 Second Cockpit

A second cockpit has been shown to be an essential part of Vis-Eval. It provides for a wingman for the basic two-ship element and thus the ability to fly a basis two-ship mission. The Vis-Eval results with a second cockpit are more representative of real world flight. It is recommended that a second cockpit be used in any future force cue evaluations.

# APPENDIX B

## RECOMMENDED PROCESS FOR CONDUCTING A FORCE-EVAL

The Force-Eval method must be designed to collect both subjective (pilot opinion) and objective (measured performance) data for determining the effects of force cues and their fidelity upon pilot control strategies, performance and training. Figure B-1 provides a block diagram of the method or process for conducting a force cueing evaluation. Starting on the left, based upon the mission, tasks to be accomplished are defined. Tasks which are believed to be force cue sensitive are highlighted for more detailed tracking during the force evaluation. Flight profiles for these tasks may also be delineated. Both the collected objective data and expert pilot opinion need to be contributors to evaluation. Initially, the feedback loops shown in would be limited to subjective inputs. However, during the evaluation both subjective and objective feedback should play a role in refinement and updating the evaluation method. Again referring to Figure B-1, there is a series of elements (in addition to the mission task/profile database) which is first established subjectively using expert pilot and technical inputs. These elements include the questionnaires, pilot debrief process, objective data requirements and instrumentation. The requirements for each of these elements is part of the method which may be further defined, refined and validated during an evaluation. Details of these elements are provided in the sections that follow.

### B-1 Force Cue Mission Tasks Data Base

This database, when fully developed, identifies the force cues associated with mission tasks including classification of the type of force cue (i.e. maneuver, disturbance, etc.) and subjective ratings of its importance. Table B-1 is an initial database, which includes potentially force cue sensitive tasks. It includes tactical combat tasks, the force cues encountered, the effects of the force cues, the frequency with which they are experienced and non-force cue sources which may be present. This table does not include cue classification. Classification will require evaluation data. Table B-2 provides a strawman for task/force cue classification. The chart categorizes the cues by both type and importance.

The mission task database when more completely developed would also describe the flight profiles and how force cues may be experienced during the different task maneuvers. A force evaluation provides an opportunity to observe, in a real-time mission simulation environment, pilot reaction to these forces. During the evaluation there should be an opportunity to expand, update and refine the mission task data base which may have been subjectively compiled at the beginning of the evaluation.

### B-2 Pilot Evaluation Questionnaire

Referring to Figure B-1, the pilot evaluation questionnaire is developed based upon the mission task/profile database. The effectiveness of this questionnaire can only be determined through its application in an evaluation. Immediately following an evaluation mission, the pilot should complete the questionnaire. The questionnaire must also be updated as a result of any changes to the mission task/profile database.

### B-3 Pilot Debrief Process

The pilot debrief is used to expand upon and detail questionnaire responses. The debriefing process should be updated during the Trial Force-Eval based upon experience gained through debriefing the operational pilots.

### B-3.1 Follow-up Pilot Interview

Following review of the recorded mission data, the training systems analysts may choose to recall the evaluation pilot to review certain aspects of the mission. During this interview, the objective data collected may be discussed with the pilot in order to sort out certain aspects of the results

### B-4 Evaluation Data Analysis

The evaluation data analysis is the process that includes compiling the subjective data from pilot questionnaires and pilot debriefing with objective data measured during pilot evaluation flights and analyzing the results. This analysis will not have full meaning until such time as the initial results are shared with the evaluation pilots during the evaluation consensus meeting. Referring to Figure B-1, the Pilot Operational Performance Data block, refers to any data available from aircraft flight test that may have a bearing on the analysis. Since it is not known to what extent, if any, such data may be available, this block is connected with a dotted line.

### B-5 Evaluation Consensus Meetings

The purpose of the evaluation consensus meetings is to reach an agreement among an evaluation team made up of training/system engineers and expert/operational pilots, to verify both the evaluation method and the results of the evaluation. It is conceivable that there may be more than one evaluation consensus meeting. Many components of the evaluation process may change as a result of information learned during these consensus meetings. This may include changes to the mission task/profiles database, objective data base measurement requirements, instrumentation, pilot debrief process, and evaluation data analysis process.

### B-6 Results and Validated Force-Evaluation

The results of the Evaluation consensus meeting and the analysis conducted prior to that meeting form the basis of the force evaluation results. Referring to Figure B-1, there are several feedback loops, which during the course of the evaluation should assist in fine tuning the results.

### B-7 Force Evaluation Data Organization

Conducting a force evaluation will result in the collecting of large amounts of both objective and subjective data. Organization of the data for analysis is extremely critical to timely data reduction. Also, an effective data management system is required for facilitating future use of the method.

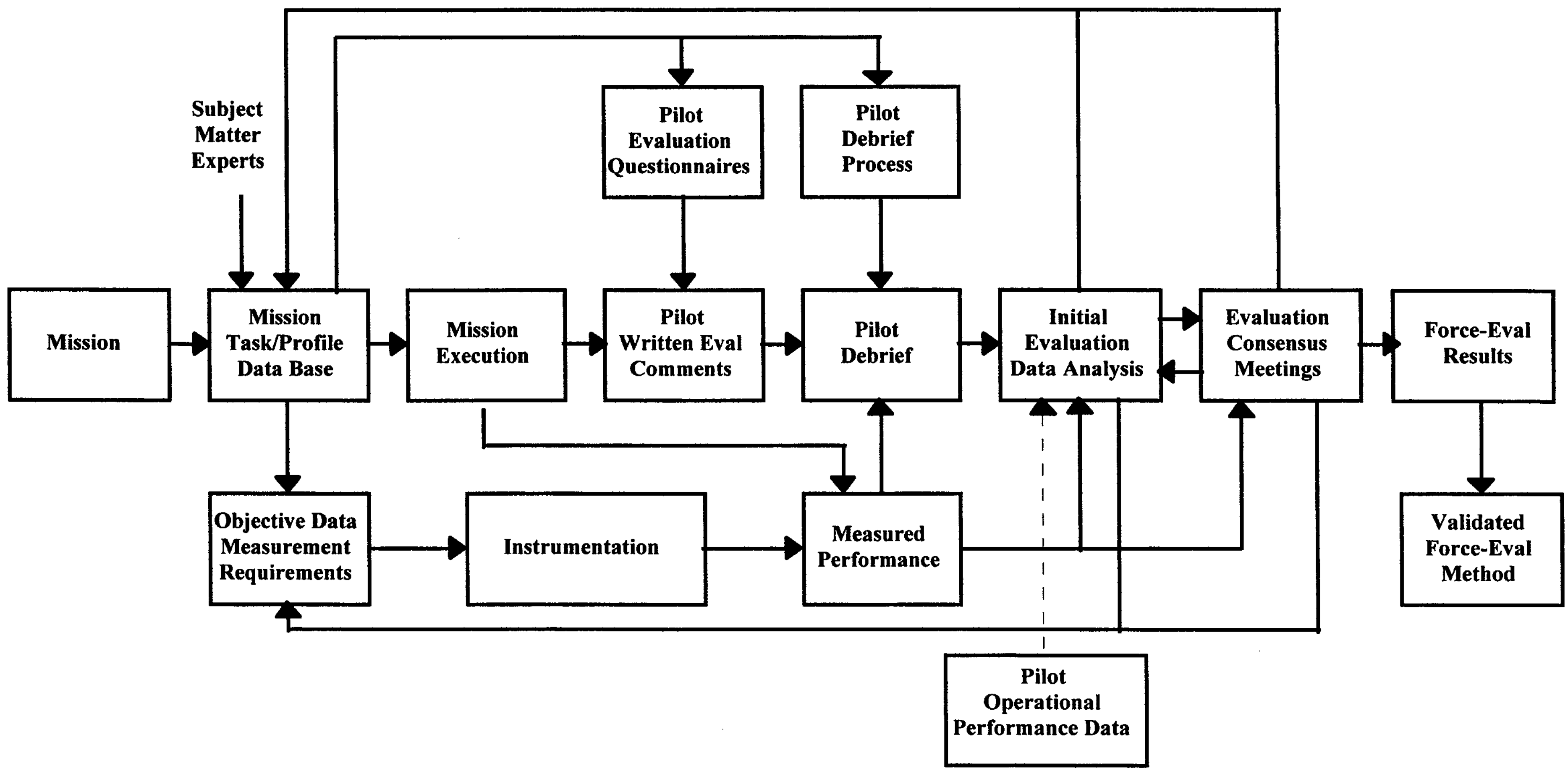


Figure B-1. Force Cueing Evaluation Method

## Table B-1. Force Cue Mission Tasks Data Base

| TASKS | TYPE FORCE CUES | WHY REQUIRED | CONDITIONS | NON FORCE CUE SOURCES |
|---|---|---|---|---|
| FORMATION<br>Close/Route | Heave/g-cue, Surge, Pitch | - Heave and surge cues provide response to the pilot of the impact of stick, throttle and speedbrake inputs, showing that his aircraft is changing not the other aircraft. Heave/G-cue provides feedback for pitch changes, closes the control loop and prevents PIO. To the wingman, roll changes are felt as heave since he is rolling along an arc away from the center of rotation of the flight lead. The lead however, senses the roll. G and g changes are used by the pilot for control of maneuvers exceeding 1 g flight. | Frequently in day, night, VFR and IFR conditions | - Airspeed is related to surge and is available on the HUD and instrument panel, but lags the surge cue. Use of this alternative may result in PIO. In addition, the airspeed of the lead may not be constant or accurately known.<br>G and g changes are available in the HUD and on the g meter but both require looking away from the lead aircraft. Use of these alternatives may result in sloppy formation. |
| FORMATION<br>Tactical<br>- Line Abreast/ Combat spread<br>- Wedge | Heave/g-cue, Surge, Roll, Pitch | - Heave, pitch, roll and surge cues provide feedback to the pilot of the impact of stick, throttle and speed brake inputs, showing that his aircraft is moving not just the other one. Closes the control loop and prevents Pilot Induced Oscillations (PIO). Roll cues provide feedback that tighten the control loop during maneuvering of the formation. Pilots use g-cues to control maneuvering of the formation during turns to ensure that all aircraft turn with similar radii to maintain the formation. Heave/g-cues also provide feedback to pitch changes. Force cues allow the pilot to keep his head out of the cockpit to clear his assigned area of the enemy.<br>Figure B 1. Force-Eval Evaluation Method | Performed frequently in day VFR conditions. | -Altitude, g-cue, airspeed and attitude are available on the HUD and instrument panel. With 6-12000 feet between aircraft and the requirement to look out for other aircraft or missiles, however, information available on the HUD or in cockpit can only be cross-checked, not used for control. Inattention to the outside world can easily result in poor formation and excessive use of fuel by wingman or may result in tactical surprise by the enemy. |

**Table B-1**
**Force Cue Mission Tasks Data Base**
**(continued)**

| TASKS | TYPE FORCE CUES | WHY REQUIRED | CONDITIONS | NON FORCE CUE SOURCES |
|---|---|---|---|---|
| THREAT REACTION<br>Air-to-Air<br>Air-to-Surface | G cue/Heave, Surge, Roll, Pitch | - G-cue/heave cues provide necessary feedback and aircraft performance during maximum performance maneuvering including accelerations at less than one g while the pilot attempts to maintain visual contact with the threat. Surge cues provide feedback that the afterburner and speed brakes are operating properly. Roll and pitch cues provide feedback on your maneuvers versus the threat and are especially important when no visual horizon is in sight (e.g., near the vertical). Heave/G-cue provides cues to pitch changes in all but low energy states. | Maneuvers against threat aircraft and missiles are performed frequently in day VFR conditions | -Once found visually, visual contact with the threat, either aircraft or missile, must be maintained during the engagement since reacquisition may be extremely difficult. As a result, cues available on the HUD or instrument panel may be of little use unless the enemy is within the field of view of the HUD. Loss of visual contact may result in the loss of your aircraft or formation to enemy action. |
| POP-UP ATTACK and WEAPON DELIVERY<br>- Individual | G-cue/Heave, Roll, Pitch, Surge | -G-cue/heave cues provide direct feedback to the pilot on proper performance of the pull up, pull down and dive recovery for pop up attacks of all dive angles and feedback on pitch changes. Roll and pitch cues provide feedback on both intentional and unintentional maneuvering during the pop up, especially during the primary offset pop up delivery when the target is well off-axis and may be difficult to locate visually. Surge cues provide feedback on the afterburner. | Pop-up attacks are the primary mode of weapon delivery for day VFR conditions. | -HUD and instrument information on these cues is available but is only usable during direct pop-ups, not during the primary offset pop-up delivery. |

**Table B-1**
**Force Cue Mission Tasks Data Base**
**(continued)**

| TASKS | TYPE FORCE CUES | WHY REQUIRED | CONDITIONS | NON FORCE CUE SOURCES |
|---|---|---|---|---|
| **POP-UP ATTACK and WEAPON DELIVERY**<br><br>**- Formation** | G-cue/Heave, Roll, Pitch, Surge | -Formation pop-up deliveries are the same as individual deliveries for the flight lead, but the wingman must maneuver relative to the leader and find the target for his own delivery. G-cue/heave cues provide direct feedback to the pilot on proper performance of the pull up, pull down and dive recovery for pop up attacks of all dive angles and feedback on pitch changes. Roll and pitch cues provide feedback on both intentional and unintentional maneuvering during the pop up delivery when the target is well off-axis and may be difficult to locate visually. Surge cues provide feedback on the afterburner. | Pop-up attacks are the primary mode of weapon delivery for day VFR conditions. | -HUD and instrument information on these cues is available but is only useable during direct pop-ups, not during the primary off set pop-up delivery. The wingman is even less able to use HUD or instrument information during the pop-up than the lead. |
| **Basic Fighter Maneuvering (BFM)**<br><br>**Air Combat Maneuvering (ACM)** | G-cue/Heave, Roll, Pitch, Surge, Lateral<br><br>Same as BFM | -G-cue/heave cues are a primary feedback cue to the pilot permitting maximum performance air-to-air maneuvering while maintaining visual contact with the opposing aircraft. They also act as feedback for pitch changes. Roll cues provide feedback to stabilize the roll axis, especially during low energy maneuvering. Pitch and lateral cues are of primary benefit during low energy maneuvering. | BFM and ACM are performed frequently in day VFR conditions. | -HUD and instrument information on g-cue, roll, pitch and yaw is available, but only during the small portion of the time the other aircraft is in the forward field of view. Since the pilot must maintain visual contact with the opposing aircraft, his line of sight is most often elsewhere. Significant loss of visual contact will result in loss of the engagement. During ACM engagements, members of the flight must acquire and track not only opposing aircraft but the friendly aircraft in his flight--an even more difficult task. |

## Table B-2 FORCE CUE IMPORTANCE RATINGS

| TYPE CUES | DISTURBANCE | | | MANEUVER FORCES | | | | |
|---|---|---|---|---|---|---|---|---|
| | VIBR | BUFF | TURB | OTHER | SHORT TERM | | LONG TERM | |
| **TASKS** | | | | | OPEN LOOP | CLOSED LOOP | POS G's | NEG G's |
| TAKEOFF | | | | | | | | |
| TAXI | 1 | | | | | | | |
| LIFTOFF | | | | | 2 | | | |
| CLIMB | | | | | | 2 | | |
| LOW ALTITUDE FLIGHT | | | | | | | | |
| MAINTAIN ALTITUDE | | | 3 | | | 2 | | |
| MAINTAIN DIRECTION | | | | | | 2 | | |
| TERRAIN AVOIDANCE | | | | | 2 | | | |
| TERRAIN FOLLOWING | | | | | 2 | | | |
| WEAPONS DELIVERY | | | | | | | | |
| EXECUTE POPUP | | | | | 2 | | 2 | 2 |
| ALIGN TO TARGET | | | | | | 2 | | |
| TARGET ACQUISITION | | | | | | | | |
| EXIT TARGET AREA | | | | visual dim | 2 | | 2 | |
| CLOSE FORMATION | | | | | | | | |
| MAINTAIN CLOSURE | | | | | | 4 | | |
| MAINTAIN VERTICAL | | | | | | 2 | | |
| OTHER | | | | | | | | |
| APPROACH STALL | | 4 | | | | | | |
| ENGINE OPERATION | 1 | | | 1 | | | | |
| DEPLOY WEAPONS | | | | 1 | | | | |

**NOTE: OTHER -** Cues such as audio (could also be sensed tactile), visual dimming, etc.

| FORCE CUE IMPORTANCE RATINGS | |
|---|---|
| 4 | IMPORTANT-WITHOUT CUE PERFORMANCE SIGNIFICANTLY DEGRADED |
| 3 | USEFUL TO PERFORMING TASK-SUPPORT/REINFORCES OTHER CUES i.e. VISUAL |
| 2 | CUE INCREASES/DECREASES WORKLOAD FOR MORE REALISTIC TRAINING ENVIRONMENT |
| 1 | MORE REALISTIC ENVIRONMENT WITH CUE-ENHANCES TRAINING |
| 0/BLANK | NO EFFECT ON TASK PERFORMANCE OR TRAINING |

# BIBLIOGRAPHY


Albery, Wm B. and Gum, Don R., AFHRL/ASM, Wright Patterson AFB OH, Kron, Gerald J, Link Div, Singer Company, Binghamton NY, Motion and Force Cueing Requirements and Techniques for Advanced Tactical Aircraft Simulation, AGARD, Conference Proceedings No 249 Piloted Aircraft Environment Simulation Techniques, December 1978.

Ashworth, B.R. and McKissick, B.T., Effects of Helmet Loader Cues on Simulator Pilot Performance, AIAA Paper 78-1573 R, 1978.

Brown, James E., etc., Visual System Operational Evaluation, ASC-TR-94-5030, July 1994

Department of Defense, COMBAT EDGE, Combined Advanced Technology Enhanced Design "G" Ensemble Equipment, T.O. 14P3-1-161, April 18, 1990.

Heintzman, Richard J, Determination of Force Cueing Requirements For Tactical Combat Flight Training Devices, Training Systems Product group, Wright Patterson AFB, OH, ASC-TR-97-5001, February 1997.

Matthews, N.O. and Martin, C.A., The Development and Evaluation of a "G" Seat for a High Performance Military Aircraft Training Simulator, Cranfield Institute of Technology, Cranfield Bedford England, 1978.

McMillan, Grant R., AAMRL, Wright Patterson AFB OH, Cress, Jeffrey D. and Middendorf, Matthew S., Logicon Technical Services, Dayton OH, Dynamic Seat Cueing With Wide Versus Narrow Field-of-View Visual Displays. AIAA-90-3128-CP, 1990.

# GLOSSARY

**Cue**. A stimulus that has acquired meaning (Caro, 1988).

**Cutaneous.** Pertaining to the skin or receptors in the skin, or to sensation mediated by receptors in the skin (Boff, 1988).

**Discrimination.** The recognition that a given stimuli or response has a meaning different from that of another stimulus or response (Caro, 1988).

**Dynamic Seat.** A simulated aircraft seat designed to use in a flight simulator which provides the pilot with a wide range of force cues such as sustained high-g force cues, vibration, and tactual cues. It may also include anti g-suit or/and lap belt actuation.

**g-Seat.** A simulated aircraft seat designed to use in a flight simulator which provides the pilot with sustained high-g force cues. Simulated seats with the additional capabilities of a dynamic seat are often referred to as g-seats.

**Haptic.** Pertaining to or arising from tactual perception based upon cutaneous and kinesthetic information. (Boff, 1988).

**Hz.** Hertz, a unit of frequency equal to one cycle per second.

**Kinesthetic.** The sense of movement and position of limbs or other body parts, arising from stimulation of receptors in the joints, muscles, and tendons. (Boff, 1988).

**Stimuli.** A physical object or event that can activate a sense organ. Stimuli are the bases for cues (Caro, 1988).

**Tactile.** Of or relating to tactual perception (touch) mediated by the cutaneous (skin) sense. (Boff, 1988).

**Tactual.** Of or relating to the sense of touch, as mediated by the cutaneous (skin) sense and/or kinesthetic (Martin, 1986).

**Vection.** Vection is an illusory sensation of motion of the self, produced by translatory and angular motions of the visual scene. (Boff, 1988).

**Vestibular Sense.** The sense mediated by the otolith organs and semi-circular canals that is concerned with the perception of head position and motion and is stimulated by acceleration associated with head movements and changes in the pull of gravity relative to the head. (Boff, 1988).

**Vestibular System.** The system comprised of the otolith organs and the semi-circular canals that mediates the perception of head position and motion. (Boff, 1988).

## LIST OF ACRONYMS

| | |
|---|---|
| A/A | Air-to-Air |
| A/G | Air-to-Ground |
| AOA | Angle of Attack |
| ALCOGS | Advanced Low Cost g-Seat |
| BVR | Beyond Visual Range |
| Combat Edge | Combined Advanced Technology Enhanced Design G Ensemble |
| EEG | |
| FOV | Field of View |
| HDD | Head Down Display |
| HOTAS | Hands On Throttle And Stick |
| HUD | Head-Up Display |
| Hz | Hertz |
| I/O | Input/Output |
| LCOSS | Lead Computed Optical Sight System |
| LOC | Loss of Consciousness |
| LOS | Line of Sight |
| MPD | Multipurpose Display |
| MRM | Medium Range Missile |
| NED | North-East-Down |
| nm or NM | Nautical Miles |
| NZ | Normal Acceleration |
| OTW | Out The Window |
| PDT | Primary Designated Target |
| PPBG | Positive Pressure Breathing System |
| PVI | Pilot Vehicle Interface |
| SA | Situation Awareness |
| SD | Situation Display |
| SRM | Short Range Missile |
| USAF | United States Air Force |
| WL | Wright Laboratory |
| WOW | Weight on Wheels |
| WPAFB | Wright Patterson Air Force Base |
| WVR | Within Visual Range |